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Fast Tuner R&D for RIA

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FAST TUNER R&D FOR RIA*

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Abstract

The limited cavity beam loading conditions anticipated for the Rare Isotope Accelerator (RIA) create a situation where microphonic-induced cavity detuning dominates radio frequency (RF) coupling and RF system architecture choices in the linac design process. Where most superconducting electron and proton linacs have beam-loaded bandwidths that are comparable to or greater than typical microphonic detuning bandwidths on the cavities, the beam-loaded bandwidths for many heavy-ion species in the RIA driver linac can be as much as a factor of 10 less than the projected 80–150 Hz microphonic control window for the RF structures along the driver, making RF control problematic. System studies indicate that for the low-β driver linac alone, running the cavities with no fast tuner may cost 50% or more than an RF system employing a voltage controlled reactance (VCX) or other type of fast tuner. An update of these system cost studies, along with the status of the VCX work being done at Lawrence Livermore National Lab is presented.

INTRODUCTION

The Rare Isotope Accelerator driver linac, as it is presently envisioned, is a heavy-ion accelerator capable of efficiently accelerating all stable or near-stable isotopes from protons to uranium. To meet the nuclear physics objectives of producing proton- and neutron-rich nuclei far from stability, the machine would be used to drive either heavy nuclei into a fast-fragmentation target or protons into an isotope separator on-line (ISOL) target. The driver is made up of a combination of superconducting accelerating structure types that are common to the heavy ion superconducting RF (SRF) accelerator community and span quarter-wave, half-wave, and spoke, as well as elliptical, cavities [1]. The combination of light and varying beam loading (~10's–100's of uA) and very high cavity quality factor ($Q \sim 10^9$) provides an engineering challenge as how one can most efficiently couple RF power into the cavities, thereby minimizing capital and operating costs.

FAST TUNER RELEVANCE TO RIA

Research and development related to the application of fast tuning on the driver and RIB linacs for RIA has the potential to decrease the capital and operating cost of the machine while increasing performance. The interdisciplinary and complex nature of coupling RF power into SRF cavities operating at narrow loaded-Q bandwidths of 10-100 Hertz demands a thorough understanding of the problem and the tuning technology base (SRF accelerators operating today typically have loaded bandwidths from 500 – 1200 Hz). Developing this knowledge base enables informed system evaluations and trade-off studies to be done to arrive at the solutions that offer the highest performance at the lowest cost. The extent to which R&D in fast tuners is supported will establish how well suited, efficient, and robust the RF control of the RIA linacs will be, which ultimately impacts the overall performance and productivity of the machine as a scientific instrument.

RF CONTROL REQUIREMENTS

To maintain stable accelerating voltage in an SRF cavity, three basic strategies are available: 1) Beam-match couple to the cavity and attempt to adapt to the microphonic-driven detuning by rapidly driving in increased generator power when the cavity detunes due to a localized microphonic excursion; 2) greatly overcouple the cavity beyond beam match with the drive coupler to increase the bandwidth; or 3) try to reduce the microphonic-driven detuning bandwidth directly.

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The first two approaches result in wasted RF power and larger capital costs for excessive installed capacity, while the third requires some sort of fast tuner. The situation is shown graphically in Fig. 1 for a 345-MHz two-gap spoke resonator. The case where the cavity is overcoupled would be for a Q_x a factor of 10 below ~1.3×10^7, and for the beam-match coupled case the dashed curve would be the generator power needed to maintain cavity fields with microphonics.

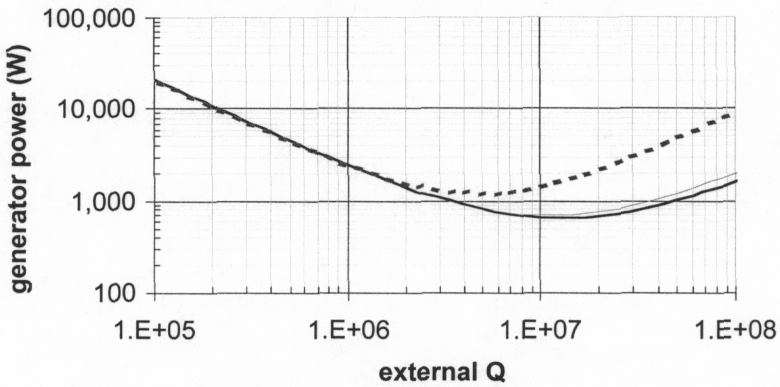


Fig. 1. Plot shows the RF generator power needed to maintain cavity fields at the desired level for a 345–MHz spoke cavity with 413 uA of beam current. The upper dashed and lower light-weight line indicate the power needed for minus and plus 40 Hz of microphonic detuning, respectively. The heavier solid bottom curve is for beam-induced detuning as well as the fast-tuner compensated microphonics case.

Microphonics

The issue of what constitutes a reasonable microphonic window is rather elusive. On lightly beam-loaded heavy-ion superconducting accelerators like ATLAS, control windows for microphonics are quoted as being around 150 Hz [2]. Discussions at recent workshops [3][4][5] have indicated that while measured microphonic excursions by a given cavity may only be 5–15 Hz, having a factor of 10 on the overall control window for the system of cavities on the linac is necessary, since the actual spread of detuning across a distribution of cavities will be larger than it is for a singular cavity. This methodology of having a modest actual detuning range, multiplied by a margin factor, shall be used for the comparisons presented in this paper.

RF SYSTEM LAYOUTS AND COST BASIS

Two conceptual RF system designs were developed for comparison purposes. The first system used overcoupling to increase the bandwidth to ameliorate the effects of microphonics. The second used some form of fast tuner to significantly reduce the microphonic-induced detuning window.

In the assessment, components were chosen appropriate to the operating conditions anticipated. In the overcoupled case, transmission lines, power couplers, and circulators needed to handle infinite voltage standing wave ratio (VSWR) conditions on a continuous wave (CW) basis. This case also required larger RF amplifiers to drive the system. The fast-tuner system was similar, except the overall system power was substantially less, thereby lessening the power handling requirements on these components and decreasing the generator size. The fast- tuner assembly and impacts on the cryogenic system were also taken into account.

Fig. 2 shows the variations of average cost in CW RF amplifiers at low power. The staircase effect suggests one would like to choose amplifier sizes to maximize cost efficiency. Fig. 3 shows how the data extends to higher power ranges using a more conventional dollar-per-Watt metric.

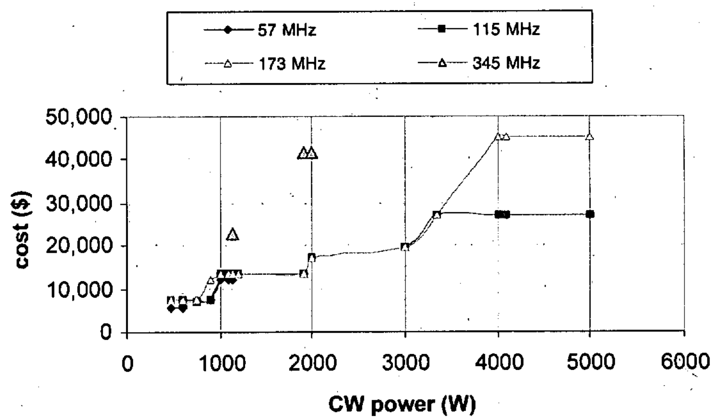


Fig. 2. Cost data for narrow-band RF amplifiers as a function of output power. The amplifiers were either Class A or AB.

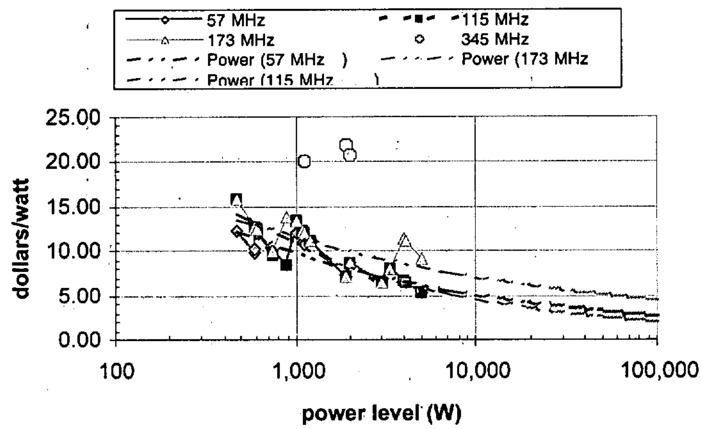


Fig 3. Cost data expressed in dollars per Watt as a function of power level. Power-function fits show how the data scales to higher power values consistent with $3–5 /Watt.

COST COMPARISONS

Applying the cost data to the two RF architecture concepts, a cost comparison was done between fast-tuning and overcoupling-compensated microphonic cases. Table 1 shows that utilizing a form of fast tuning can reduce the installed RF power required by as much as a factor of 3 and reduce the capital cost by a factor of 1.5, potentially saving on the order of 6 million dollars.

Cavity Type	Overcoupled Case		Fast-Tuner Compensated	
low β (MHz)	installed RF power (W)	section cost (k$)	installed RF power (W)	section cost (k$)
57.5	160,000	2,155	30,000	1,160
115	225,000	2,424	45,000	1,576
172.5	520,000	7,522	104,000	3,642
345	160,000	5,508	160,000	5,098
totals:	1,065,000	17,609	339,000	11,476

Table 1. Results of a cost comparison exercise between overcoupled and fast-tuner compensated approaches for handling microphonic detuning on the low-beta section of the RIA driver linac. In the 345–MHz case, while the installed power is the same, the costs differ since the RF match is better, resulting in lower VSWR operation.

Evaluations were also made on the impacts of using fast tuning on the elliptical cavity portions of the linac, which indicate a potential reduction in installed RF power of a factor of 5.1, and a cost savings on the order of 11 million dollars could be realized. Further development would be needed to extend the present work to 805 MHz elliptical cavities.

FAST TUNING

Fast-tuning SRF cavities to reduce the effects of microphonic detuning has been under development for over 20 years. Work at KEK on TRISTAN using piezoelectric crystals, at CERN on LEP using magnetostrictive bars, and at ANL on ATLAS using voltage controlled reactance (VCX) tuning has been invaluable in establishing a technology base for fast tuning. Of these three approaches, VCX has had the most success in terms of reliable operation and the demonstrated robustness of the technology encourages efforts to develop it further. Recent advances in piezo and magnetostrictive materials offers the potential for these approaches to be more viable than they were on earlier machines, and is driving a revived interest in these areas. With the importance of fast tuners for RIA, and the variety of cavities that will need fast tuning, developing experience with and advancing tuner designs of these three approaches will be important.

Advancing the design of the voltage controlled reactance fast-tuner concept that was originally developed and applied on ATLAS has been pursued as part of the R&D work being done by LLNL. While a portion of the driver linac has similar parameters to ATLAS, as shown in Fig. 4, development work is needed to advance that design to the higher frequencies (345 MHz) and stored energies in RIA. Switching losses in the liquid nitrogen coolant will ultimately limit the practical upper bound of stored energy in terms of cryoplant size that can be tuned with this approach, also shown in figure 4.

The original Argonne approach utilized 10 PIN-type RF-switching diodes combined with lumped inductive and capacitive elements, all immersed in liquid nitrogen, to change the reactive impedance of the cavity to effect a rapid change in the resonant frequency of the system of the cavity plus tuner. By switching the PIN diodes from full conduction to full isolation at 25 kHz, the desired precise accelerator frequency can be approximated by the vector sum of the cavity voltages corresponding to the on and off state of the tuner. To compensate the observed microphonic detuning windows on ATLAS, 15–20 kVAR (voltage-ampere reactive) of reactive power was switched.

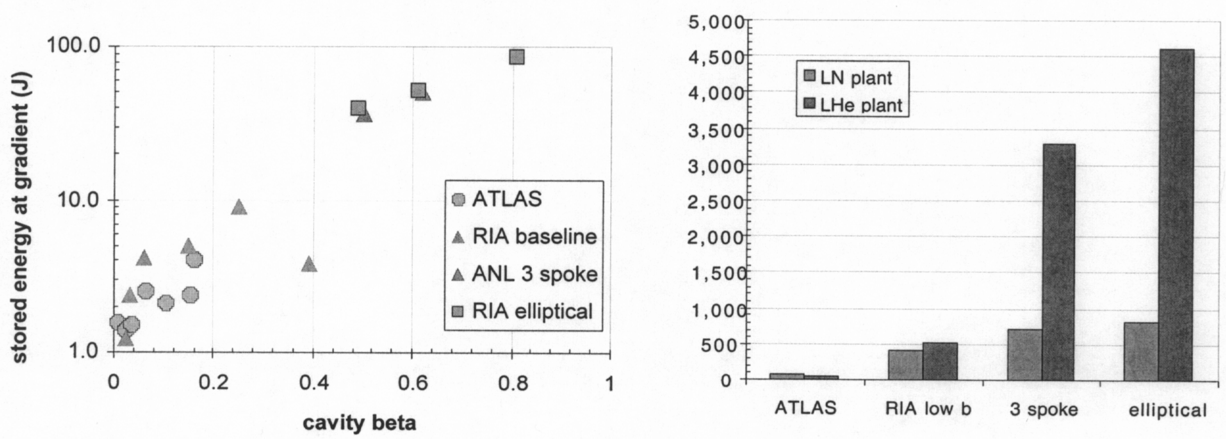
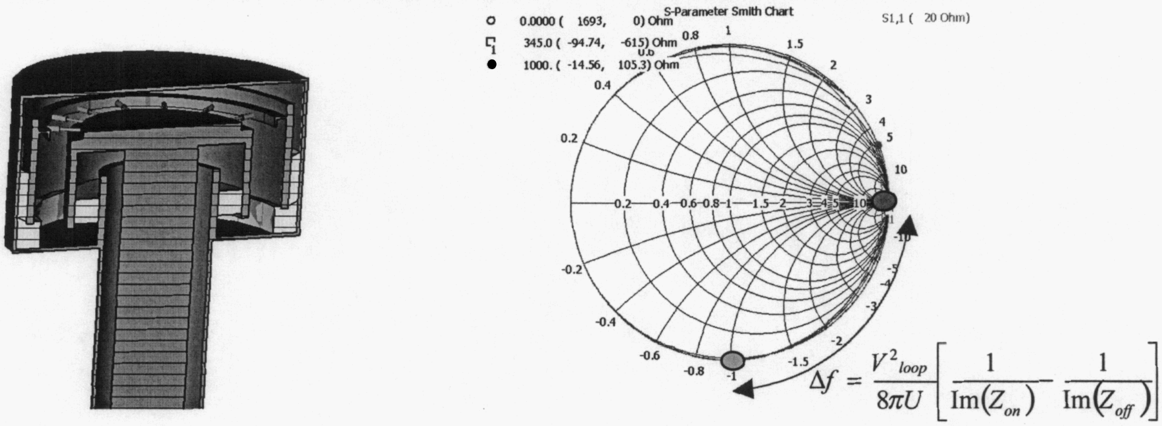


Fig. 4. The left plot showing the stored energy at gradient in various cavities as a function of the particle beta they are designed to accelerate. The low-β driver cavities have similar parameters to ATLAS structures. The right plot shows estimates of the LN and LHe cryoplants that needed.

This approach has worked for frequencies up to 97 MHz. To extend the technology to higher frequency and reactive power ranges, a different design approach is being developed and evaluated that utilizes distributed inductive and capacitive elements in a transmission-line configuration, but keeps the same proven lumped-element, high-power PIN diodes used originally. The new configuration offers the possibility of being more broadband for higher frequencies than an approach relying on lumped elements and is also potentially extendable to switching reactive power levels up to75–100 kVAR by readily adding larger numbers of PIN diodes. A drawing of the distributed element approach being investigated and its response is shown in Fig 5.



$$\Delta f = \frac{V^2_{loop}}{8\pi U}\left[\frac{1}{\mathrm{Im}(Z_{on})} - \frac{1}{\mathrm{Im}(Z_{off})}\right]$$

Fig 5. On the left is a drawing of a distributed element approach for a high-frequency VCX. The light components are ceramics acting as capacitors, and the PIN diodes are the circumferentially distributed cylinders. The region where the PINs are located would be filled with liquid nitrogen. The right shows a Smith chart with the on and off impedance states from switching the PIN diodes.

FUTURE WORK

Future work in fast tuners would focus on furthering the design of the VCX concept to take the distributed element approach to the prototype stage for testing and evaluation on a 345 MHz spoke cavity. Work would also continue on a system evaluation of piezo, magnetostrictive, and VCX tuners on the RIA driver and RIB linacs related to RF generators, power couplers, and delivery systems, and would include data being generated at both ANL and MSU in their cavity test programs. These efforts would be directed toward developing an overall RF power, fast tuner, and transmission-line conceptual design that could be interfaced with the control system concept to evaluate overall operability of the accelerators.

CONCLUSIONS

The light beam loading conditions envisioned on the RIA driver linac offer unique challenges and opportunities in efficiently coupling RF power into superconducting cavities. Studies have shown that appreciably less installed RF power is needed when a fast tuner is used to compensate microphonics.

REFERENCES

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[3] LLRF Control Workshop, Jefferson Lab, Newport News, VA, April 25–27, 2001.

[4] Spoke Cavity Workshop, Los Alamos National Lab, Los Alamos, NM, Oct. 7–8, 2002.

[5] Second RIA Driver Linac Workshop, Argonne National Lab, Chicago, IL, May 22–24, 2002.